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Original scientific paper

A Novel Gearbox Strength Check Method by Finite Element Analysis

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Abstract: In order to meet the design requirements of gearbox for different gears, a novel method to verify bolts and gearbox housing is applied, which reduced the time and cost of experimental testing. The finite element analysis of this article is divided into two parts. Firstly, the axial force of the bolt is calculated by finite element method, and the bolts are verified according to VDI2230 standard. Secondly, the force of the gearbox housing is calculated and the strength of the gearbox housing in different gears is verified. Results show that the maximum axial force exerted on the bolt is 4761.8N at the hole 16. The maximum stress value of the gearbox is 234.2 MPa in the first gear state, which closes to the tensile strength 240 MPa. The maximum stress value of the improved gearbox housing is reduced to 133.9 MPa, meeting the usage requirements. In addition, this article established a finite element verification process for the gearbox housing. Although the grid size and boundary conditions apply only to this type of gearbox, the analysis process is applicable to the static strength verification of any gearbox housing.

Keywords: gearbox; finite element analysis; strength check

1 INTRODUCTION

A certain type of gearbox is widely used in a grader, wheel loader and crane. When the vehicle is running in different roads, the gearbox is susceptible to vibration and shock. The components of the gearbox have a large force difference under full-load, no-load and variety gears. Therefore, the strength of gearbox housing must meet the operation requirements of different conditions. The overall design of gearbox housing usually depends on experimental data obtained from the test bench or various road on-site tests. However, this process takes a lot of time, and it not only consumes plenty of labor and financial resources, but also affects the design schedule and increases design cost.

With the development of technology, finite element method (FEM) analysis has attracted more and more attention and concern [1, 2]. Miltenovic A. et al. [3] predicted thermal stability of a gearbox by applying the finite element method, and proposed a new procedure for the prediction of heat generation in the crossed helical gear transmission. Some scholars [4-6] reduced the gearbox radiated noise by increasing the housing stiffness. Zoltan et al. [7] presented an example of how the design of a gearbox housing can be improved by using Finite Element Analysis. The work exposed the way the natural frequencies are influenced by the housing material. A lot of work [8-15] on dynamic behaviors of gearboxes has been done. But few studies have been focused on the static strength check of gearbox for construction machinery.

This article verifies the strength of the gearbox model. Firstly, the strength of the bolts on the gearbox housing is checked. Secondly, the stress distribution of the gearbox housing in each gear is calculated. Finally, based on the stress distribution of the gearbox housing in the maximum stress gear, improvement plans are proposed for weak positions, which increase the bearing capacity of the gearbox and meet usage requirements.

2 THE STRENGTH CHECK OF BOLTS

The 3D model of gearbox, including gearbox housing (blue), torque converter (yellow) and end cup (white), is shown in Fig. 1. The force applied to the gearbox housing is produced from gear mesh; it is transferred to the housing form the bearing. As a design and analysis software of transmission systems, MASTA computes bearing force according to the set working condition. The detailed steps of acquiring bearing force from the model are as follows:

1. Establishing the transmission system model of wheel loader.
2. Importing a finite element model of housing with condensation nodes into Masta.
3. Connecting the transmission model and gearbox housing with mesh.
4. Setting the working conditions and calculating the model.

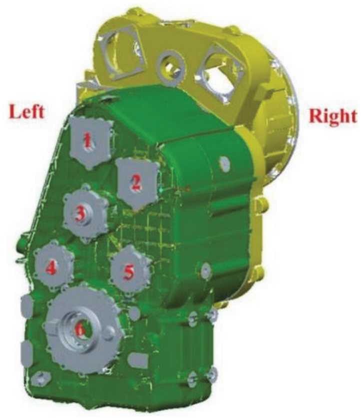


Figure 1 The 3D model of gearbox

The transmission system model with housing is shown in Fig. 2.

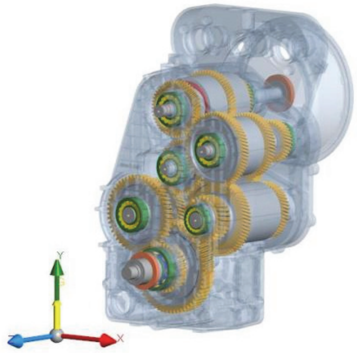


Figure 2 The wheel loader's masta model

The gearbox housing (transparent part) is connected to transmission system (physical part). Different from the traditional method of calculating bearing force, the Masta software considers the influence of housing deformation on transmission system, a more precise bearing force can be obtained, and the force exerted on housing is mainly composed of radial and axial forces at the bearing bore, as displayed in Tab. 1. It can be seen that the Maximum force is in the bearing bore 5 with the first gear.

Table 1 The bearing force of each gear

Forward	**Left**	***x* / kN**	***y* / kN**	***z* / kN**	**Right**	***x* / kN**	***y* / kN**	***z* / kN**
1st	1	4.91	5.86	1.96	1	8.89	5.19	–7.21
	2	–8.46	–1.84	4.46	2	–25.67	7.71	–7.25
	3	30.84	12.09	13.19	3	25.43	–15.81	–16.66
	4				4			
	5	–80.89	9.39	21.66	5	–14.86	–5.84	–18.36
	6	35.25	–3.56	5.19	6	24.82	–12.93	3.03
2nd	1	10.31	8.67	3.48	1	2.10	0.19	–8.11
	2	–13.467	–4.60	3.81	2	–20.04	12.83	–7.42
	3	5.77	2.94	11.66	3	40.61	–10.13	–11.66
	4				4			
	5	–29.82	8.63	11.50	5	–25.76	–10.20	–7.41
	6	17.79	–1.80	2.48	6	12.49	–6.52	1.67
3rd	1	3.50	4.15	1.39	1	6.15	3.57	–5.09
	2	–6.00	–1.26	3.12	2	–18.05	5.39	–5.09
	3	3.95	2.03	8.07	3	27.98	–6.97	–8.07
	4				4			
	5	–20.50	5.94	7.92	5	–17.75	–7.02	–5.10
	6	12.25	–1.24	1.67	6	8.59	–4.48	1.17
4th	1	10.30	8.65	3.48	1	2.10	0.19	–8.10
	2	–13.38	–4.66	3.79	2	–20.10	12.89	–7.40
	3	23.73	–23.04	13.20	3	19.16	–26.19	–16.76
	4	–30.84	2.87	9.31	4	–9.32	3.76	–2.71
	5				5			
	6	11.86	19.66	3.83	6	6.48	5.85	1.36
Reverse	1	2.24	–2.53	12.72	1	19.96	–6.57	–5.43
1st	2				2			
	3	–12.93	–28.20	12.74	3	–24.73	6.49	–9.59
	4				4			
	5	36.93	–23.85	11.56	5	6.23	5.42	–14.55
	6	–15.84	17.19	–2.60	6	–11.92	32.02	–4.84
2nd	1	1.58	–1.78	8.90	1	13.97	–4.56	–3.80
	2				2			
	3	–1.39	–4.23	6.32	3	–22.05	–4.26	–6.32
	4				4			
	5	9.54	–14.82	4.60	5	7.90	12.73	–7.14
	6	–5.58	6.14	–1.02	6	–3.97	10.79	–1.53

The analyzed model consists of gearbox and torque converter housing which are connected by bolts. In order to analyze the strength of the housing, the strength check of bolt must be done first. There are 34 bolt holes distributed on the end surface of housing as shown in Fig. 3. Firstly, the axial force of all bolts for each working condition is calculated, and then the bolt under maximum tension force is checked by FEM.

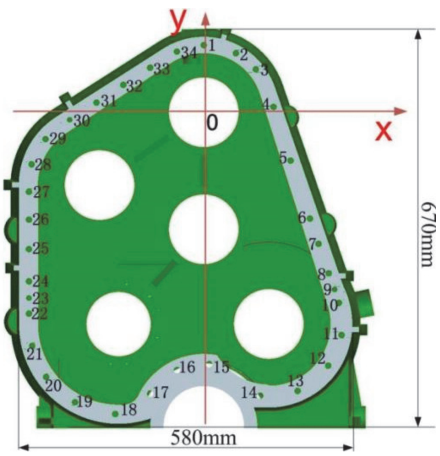


Figure 3 The position of the bolt hole

2.1 Calculation of the Axial Force of Bolt

According to the positions of bolt holes and bearing holes, 39 nodes representing them are created. Connect these nodes, to build 2D meshes model with a size of 1100 × 850 mm. Create the BEAM element to simulate the tensile state of bolt, one end is linked to the node of bolt hole, the other end is fully constrained exert to the other end. Next, the axial forces are applied to the node of each bearing hole.

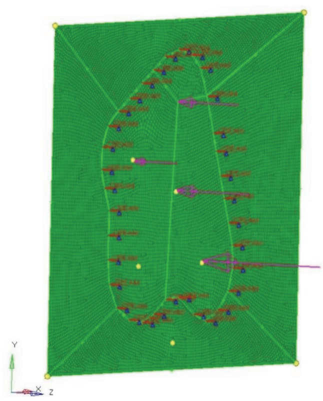


Figure 4 The finite element model of simulation stretched bolts

The finite element model and boundary conditions are shown in Fig. 4, which consists of 16118 nodes and 16249 tetras elements. The maximum bolt force of each gear is displayed in Tab. 2; it is seen that the position of maximum tension is in bolt hole 16 of the first gear forward, and the tensile force value is 4761.8 N.

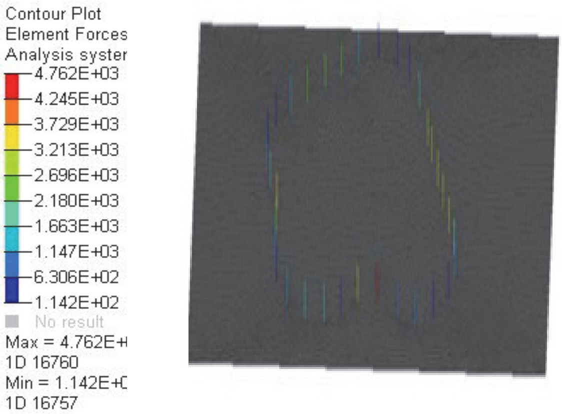


Figure 5 The result of stretched bolts for 1st gear

Table 2 The maximum bolt force for each gear

	Gears	Position of max force	Force / N
Forward	1st	16	4761.8
	2nd	5	1972
	3rd	16	2758.3
	4th	16	2160.4
Reverse	1st	16	3542.3
	2nd	17	2725.7

2.2 Checking Process of Bolts

The checking process of bolts are using VDI2230 standard. The shear force of bolt can be given as follows:

$$F_q = \sqrt{F_{qx}^{\ 2} + F_{qy}^{\ 2}} \tag{1}$$

where F_{qx} is the shear force of x direction, F_{qy} is the force stress of y direction.

The minimum clamping force of bolt is:

$$F_{\ker f} = F_q / u \tag{2}$$

where u is the friction coefficient between clamping elements.

The intercalation capacity of bolt is given by the formula:

$$f_z = nf_{z1} \tag{3}$$

where n is the number of clamping face, $n = 2$, and f_{z1} is the intercalation capacity on one side.

Then, the loss of pre-tightening force is

$$F_z = f_z * \varphi_k / \sigma_p \tag{4}$$

where, φ_k is the force coefficient, σ_p is the elastic deformation of clamping.

Calculation of axial force on screw thread supplementary force can be given as follows:

$$F_{sa} = \varphi_n / F_A \tag{5}$$

where, φ_n is the additional force coefficient, F_A is the axial force.

Calculation of axial force on clamp supplementary force can be given as follows:

$$F_{pa} = F_A - F_{sa} \tag{6}$$

where, F_A is the axial force.

The pressure of clamping element is:

$$P = F_{sp} - A_p \tag{7}$$

where, $A_p = 3.14 * d_k^{\ 2}$, d_k is the screw inner diameter.

M12 with grade 10.9 are used to connect the housing of gearing, the parameters of bolt are shown in Tab. 3 below.

Table 3 The parameters of bolt

d_k / mm	d / mm	d_1 / mm	I / mm	I_1 / mm	B / mm	P / mm	$\sigma_{0.2}$ / N/mm²
9.85	12	10.86	80	54	26	1.5	640

d: nominal diameter, d_1: screw diameter, I: bolt length, I_1: screw length, b: length of thread, p: pitch, $\sigma_{0.2}$: yield strength.

The strength checking formula of bolt is

$$F_{sa} \le 0.1\sigma_{0.2} A_S \tag{8}$$

where, A_S is the screw thread stress.

Each parameter is shown in the Tab. 4 below.

Table 4 The parameter of bolt and checking

F_{qx} / N	F_{qy} / N	F_A / N	u	f_{Z1}	φ_n	A_S / N/mm²
18452	37133	4762	0.12	10	0.12	84

Substitute all the parameters into the formula, $F_{sa} = 571.44$ N , $0.1\sigma_{0.2} A_S = 4.39 \times 10^6$ N .

3 THE STRENGTH CHECK OF HOUSING

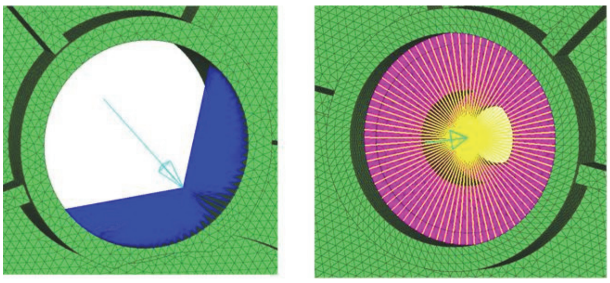
The 3D model of the housing structure is introduced into the hypermesh software. Considering the calculation time and accuracy, set the size of the chamfer, fillet and small tips mesh unit to 2 mm, and the rest mesh size is 5 mm. Since the strength check of the bolt has been completed, the bound contact is arranged between the gearbox housing and torque converter housing, as well as gearbox housing and end cup. The material property is shown in Tab. 5.

Table 5 The material property of HT250

Elastic modulus / MPa	Poisson ratio	Density / kg/mm³	Shear modulus / MPa
$1.38e^5$	0.156	$7.28e^{-6}$	$5.98e^4$

The main loads acting on the gearbox are radial and axial force at the bearing holes. When the gearbox operates in different gears, the loads on housing are different in magnitude and direction. In each bearing of the gearbox housing, the load is transmitted to the housing through the bearing outer ring or the bearing chock, which belongs to the uniform surface load. Therefore, the radial force can be equivalent to the cosines pressure within 120° [12] of the bearing hole, and the axial force can be equivalent to the uniformly distributed load. Based on Saint-Venant Principle, the radial and axial force are applied to a semicircular rigid element perpendicular to the radical force and a circular rigid element on end surface of end cap respectively (Fig. 6).

According to the assembly relationship between gearbox and vehicle, the left and right sides of the gearbox and the bolt holes on the end face of torque converter are set as full constrains. The displacement and stress of gearbox housing for each gear are carried out by FEM. For gears with large stress and deformation, refine the mesh and recalculate the housing strength. The material of gearbox housing is gray casting, the maximum principal stress should be checked to verify the strength. The tensile strength of the HT250 is 250 MPa.



(a) (b)

Figure 6 The radial and axial force exerted to the rigid element respectively

4 RESULT

The displacement and stress results of gearbox housing for each gear are performed in Figs. 7 to 12. It is known that the stress and displacement value of the 1st forward are the largest. The position of maximum stress value is at the top right-hand corner of the bearing hole 5, and the maximum displacement value is 0.21 mm, which is in the middle between bearing hole 3 and bearing hole 5.

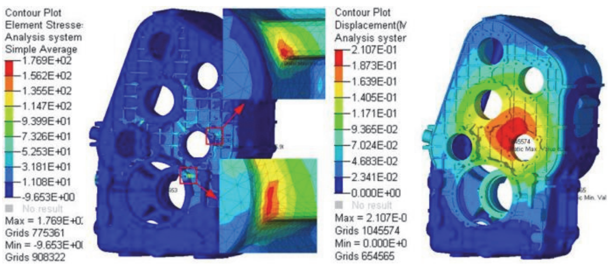


Figure 7 The displacement and stress nephogram of gearbox in 1st forward

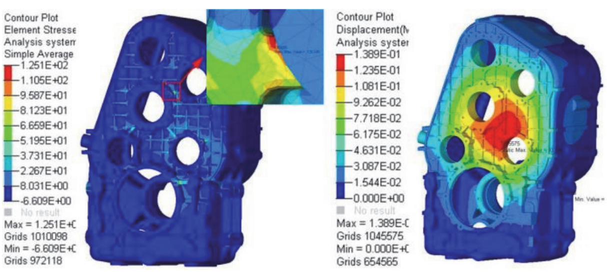


Figure 8 The displacement and stress nephogram of gearbox in 2nd forward

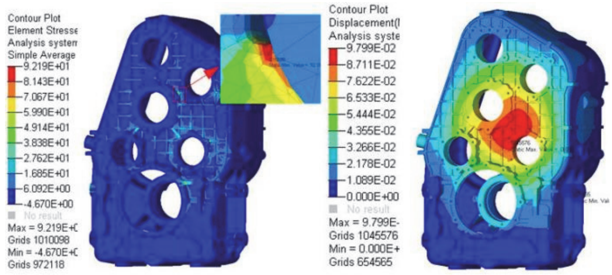


Figure 9 The displacement and stress nephogram of gearbox in 3rd forward

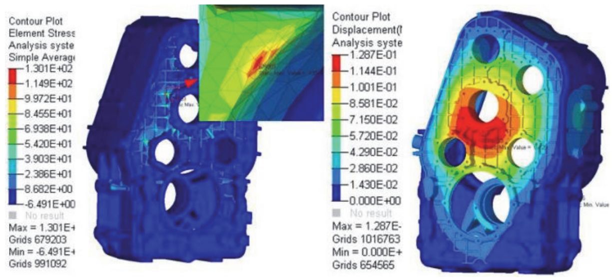


Figure 10 The displacement and stress nephogram of gearbox in 4th forward

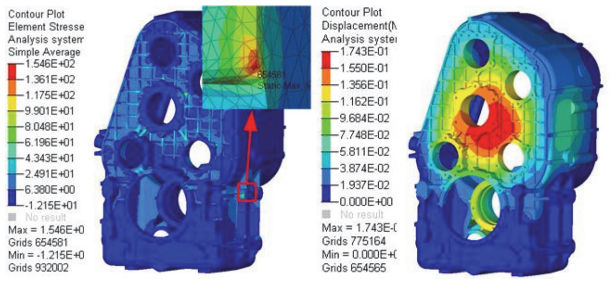


Figure 11 The displacement and stress nephogram of gearbox in 1st reverse

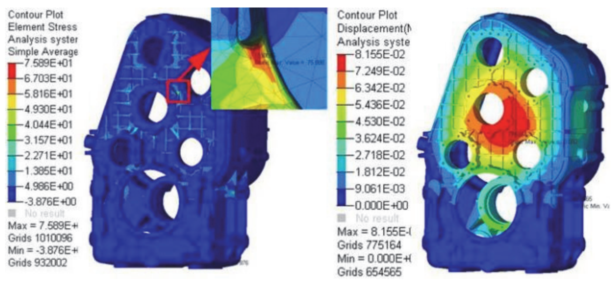
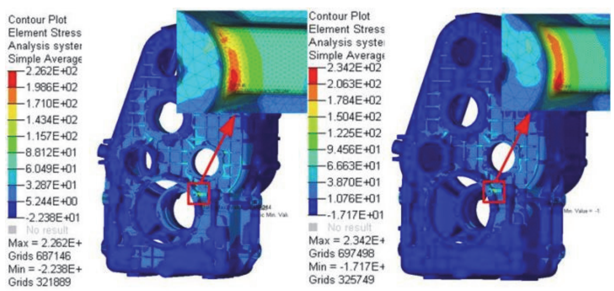


Figure 12 The displacement and stress nephogram of gearbox in 2nd reverse



a) b)

Figure 13 The stress results of the model with mesh refining (a: 1 mm; b: 0.5 mm)

The mesh refinement model at the maximum stress value is recalculated. The growth tendency of the value of stress is obvious when the size changes from 5 mm to 1mm. But when the grid size changes from 1 mm to 0.5 mm, the stress value does not increase obviously as shown in Fig. 13, the real result is 226 MPa. The model needs to be improved since the maximum stress value is close to the material tensile strength. In order to improve the structural strength of gearbox, two changes have been made. One is to fill the groove on both sides of bearing hole 5, and the other is to increase the fillet radius and width of reinforcement rib in the upper right corner of bearing hole 6. The model comparison before and after modification is shown in Fig. 14. The maximum stress value of modified model is 133.9 MPa, which is much lower than the tensile strength, and the maximum displacement is reduced from 0.21mm to 0.175 mm (x: 0.163 mm, y: 0.056 mm, z: 0.159 mm) as shown in Fig. 15.

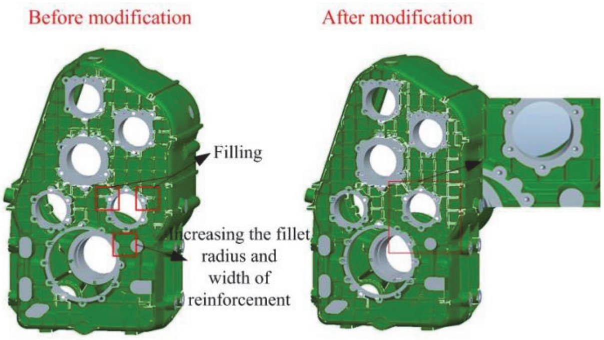


Figure 14 Comparison of before and after model modification

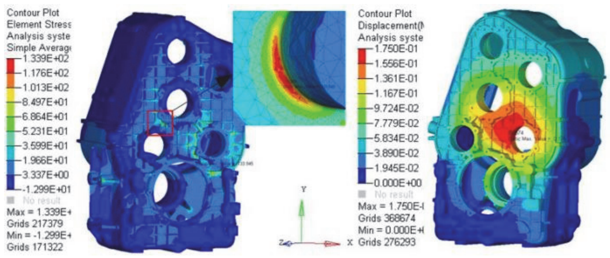


Figure 15 The results of stress and displacement for the modified model

5 DISCUSSION AND CONCLUSION

The process of strength check of gearbox housing by FEM is shown in Fig. 16. The results of finite element calculation need to be judged according to the actual situation, which requires the accumulation of rich mechanical knowledge and experience. The results are more realistic if the results do not change much before and after mesh refinement. However, the stress will increase constantly when the sharp corner at the non-circular part is subdivided. Therefore, the correct result cannot be obtained. If the real stress results are needed, the stress can be calculated by extrapolation. In other words, the mesh is subdivided at a certain distance from the closed angle to obtain the accurate stress results near it. Then, the stress at this point is extrapolated according to the distance between these points and the inflection point.

The change of stress value caused by mesh refinement may be induced by singular points, which are produced by sharp corners or boundary constraints (including contact) of the structure. This is an inherent defect of finite element theory. Strictly speaking, the singularity will occur as long as there are sharp corners in the structure. The difference between stress concentration and singular point is that a convergence result is obtained after mesh refining for stress concentration, However, for singular points, the stress value is increasing no matter how fine the mesh is. Whether the stress concentration and singular point need to be concerned depends on the specific situation.

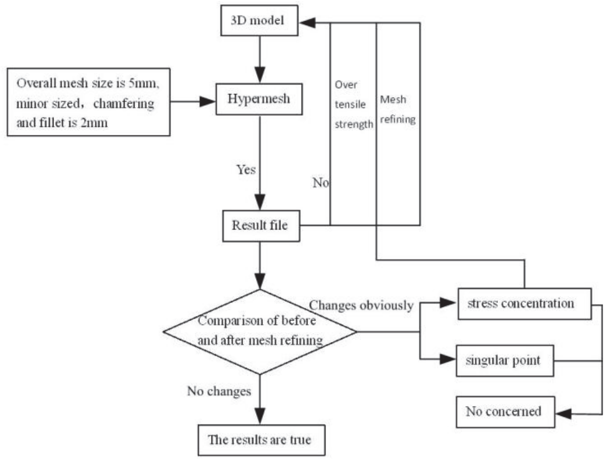


Figure 16 The flow chart of strength check of gearbox housing by FEM

The finite element results are affected by many factors. There will be some subtle difference in the analysis procedure for everyone, which will lead to inconsistent calculation results. The mesh size and boundary condition in this paper are merely applicable to the model of this work. However, the analysis flow is a reasonable standard for any static strength check.

The gearbox strength is enhanced by filling the grooves near bearing hole 5, and increasing the fillet radius and rib plate width below bearing hole 5. The stress value reduces from 234.2 MPa to 133.9 MPa, which meets the usage requirements. The limitation of this article is that it only verifies the stress distribution of the gearbox housing in different gears.

The target of gearbox application is engineering vehicles, which encounter impacts constantly during driving. Therefore, the next step is to conduct force analysis on the gearbox under frequent impacts and verify the gearbox housing additionally.

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